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We present a predictive warped model of flavor, cut off at an ultraviolet scale $\mathcal{O}(10^3)$ TeV, called the "Little Randall-Sundrum (LRS)" model. This model corresponds to a volume-truncation, by a factor $y \approx 6$, of the RS scenario and is holographically dual to dynamics with number of colors larger by y. With separate gauge and flavor dynamics, several unwanted contributions to precision electroweak, $Zb\bar{b}$, and flavor observables are suppressed in the LRS framework, compared with the corresponding RS case. The LRS truncation leads to a significant enhancement of the clean (golden) di-lepton LHC signals, by $\mathcal{O}(y^3)$.

The following is based on a talk delivered by the author at ICHEP 2008, July 29-August 5, 2008, Philadelphia, PA, USA. The source of material for this talk is Ref. [1], where more details and references can be found.

The Randall-Sundrum (RS) model [2] was originally proposed to explain the enormous hierarchy between the inferred scale of gravity $M_P \sim 10^{19}$ GeV and the Standard Model (SM) weak scale of order 1 TeV. The RS model is based on a slice of warped AdS_5 geometry, bounded by UV (Planck) and IR (TeV) Minkowski branes. The geometry provides an exponential redshift as one goes from the UV brane, characterized by a fundamental scale $M_5 \sim M_P$, to the IR brane characterized by $e^{-kr_c\pi}M_5 \sim$ TeV, for $kr_c\pi \approx 35$. Here, k is the curvature scale and r_c is the radius of compactification. Thus, the hierarchy is generated exponentially, using natural parameters. In the original model, all the SM fields were placed at the IR brane and the main signature of the model was a tower of TeV-scale spin-2 resonances, the Kaluza-Klein (KK) gravitons [3].

Later, gauge fields [4, 5] and fermions [6] were placed in the 5D bulk, leading to an interesting model of flavor [7] with TeV scale signatures. Here, using 5D fermion masses, heavy fermions are localized towards the IR brane and light fermions are localized towards the UV brane. However, a realistic model of flavor has very challenging signatures, as the light fermions, such as electrons, end up having small couplings to the KK modes. This suppresses production and clean di-lepton signals at colliders. In addition, there is significant tension between precision data and TeV-scale warped flavor models.

Tree level oblique S and T corrections in RS models with bulk flavor, assuming no extra symmetry, are given by [8]

$$S_{tree} \approx 2\pi\,(v/\kappa)^2 \tag{1}$$

and

$$T_{tree} \approx \frac{\pi}{2\cos\theta_W^2}(v/\kappa)^2(kr_c\pi)\,, \tag{2}$$

where $\kappa \equiv e^{-kr_c\pi}k$ is the KK scale and $\cos^2\theta_W \simeq 0.77$.

Agreement with precision electroweak data requires $|S| \sim |T| \sim 0.1 - 0.3$. Taking $m_{KK} \approx 5$ TeV leads to $(S,T) \approx (0.1, 1.1)$, from the above formulas, in the RS model. The large correction to T_{tree} is from tree-level mixing of the gauge KK tower, induced by electroweak symmetry breaking (EWSB), enhanced by $kr_c\pi \approx 35$.

Here, one can then see that the truncation of the RS model by decreasing the value of $kr_c\pi$ can be helpful in reducing the tension between T_{tree} and EW data, as this will reduce the strength of KK tower mixing caused by EWSB. If $kr_c\pi = 6$ is assumed, one can still generate a hierarchy between a *flavor scale* $M_5 \sim 1000$ TeV and the weak scale, in a Little Randall-Sundrum (LRS) model [1]. This flavor scale is large enough to address most if not all constraints from precision data. Here, we define the truncation factor

$$y \equiv \frac{kr_c\pi|_{RS}}{kr_c\pi|_{LRS}}, \tag{3}$$

and for our choice of scales $y \approx 6$. It is assumed that the truncation in the LRS model leaves flavor physics unchanged, corresponding to keeping the 5D Yukawa coupling λ_5 and IR profiles of fermions at their RS values.

Equation (1) suggests that the LRS value of S_{tree} does not change. This is explained by noting that this quantity is basically a result of universal shifts in light fermion couplings to gauge fields, induced by KK tower mixing of gauge fields, proportional to $\sqrt{kr_c\pi}$. However, the light fermion coupling to gauge KK modes is propotional to $1/\sqrt{kr_c\pi}$. As the net effect comes form a product of these factors, truncation leaves S_{tree} unchanged.

Note that there are also cutoff scale and UV-sensitive loop contributions to T that would push the KK masses to 10 TeV or more. These contributions, as well as T_{tree}, can be eliminated with the assumption of a bulk $SU(2)_L \times SU(2)_R \times U(1)_X$ custodial symmetry [8], allowing $m_{KK} \gtrsim 3$ TeV, in both RS and LRS scenarios.

Next we will address non-oblique and flavor data, where more significant improvements can be obtained in the LRS framework. By keeping the fermion IR-profiles at their RS value and λ_5 unchanged under truncation, the LRS model has the same level of flavor non-universality as its RS counterpart. However, as the KK-mediated effects get truncated with reduced $kr_c\pi$, non-universal effects get suppressed within the LRS construct. Two examples of these effects are contributions to $Zb\bar{b}$ coupling and $\Delta F = 2$ processes.

Constraints on $Zb\bar{b}$ coupling require non standard fermion representations under the custodial symmetry, in addition to a Z_2 symmetry [9], so that $m_{KK}^{RS} \sim 3$ TeV is allowed; otherwise, $m_{KK}^{RS} \gtrsim 5$ TeV [8]. Without the custodial symmetry, a number of contributions to $Zb\bar{b}$ arise. One is from the KK-tower mixing due to EWSB and the enhanced coupling of the gauge KK modes to IR-localized b_L. These corrections are proportional to $kr_c\pi$ and since the IR fermion profiles are kept fixed, get suppressed in the LRS scenario.

The second type of correction to $Zb\bar{b}$ is due to $\mathcal{O}(1)$ mixing between b_L and the exotic $SU(2)_R$ partner of t_R [10]. This contribution is absent if t_R is in a representation that is a $SU(2)_{L,R}$ isosinglet [9]. Note that without a bulk custodial symmetry, there is no exotic t_R partner. A third type of correction to $Zb\bar{b}$ from the mixing of the KK modes of b_R and the b_L zero mode is not truncated in the LRS model and proportional to $[1/m_{KK}(b_R)]^2$. Requiring corrections to $Zb\bar{b}$ coupling below 0.3% then yields $m_{KK}(b_R) \gtrsim 4$ TeV. However, we note that $m_{KK} \gtrsim 3$ TeV for gauge fields can accommodate this bound on the KK modes of b_R, in the LRS framework, for a realistic set of fermion profiles [1]. Therefore, all of the above constraints from $Zb\bar{b}$ can be satisfied for gauge sector $m_{KK} \gtrsim 3$ TeV, without any custodial symmetries (however, the T parameter would still require protection).

We now consider the strongest constraints on generic bulk RS models, from $\Delta F = 2$ processes, due to tree level exchange of KK gluons. The most stringent bound comes from excessive contributions $\delta(\epsilon_K) \propto kr_c\pi$ to ϵ_K from $(V - A) \times (V + A)$ operators [11, 12], requiring $m_{KK}^{RS} \gtrsim 20$ TeV; this bound is subject to roughly 30% uncertainty [13]. In the LRS case, this contribution is suppressed by y. This suppression is likely not enough to allow for warped KK mode discovery at LHC and may require extra model building to bring the mass scales closer to the TeV regime.

Phenomenology: The LRS truncation leads to significant improvements in the LHC reach for the KK modes, because: *(i)* Typically broad states [15] become narrower by a factor $y \sim (0.2/0.08)^2$, *(ii)* branching ratio (BR) into light fermions such as e^+e^- increases by a factor y^2, *(iii)* from *(i)* and *(ii)* it follows that the signal $\mathcal{S}$ gets enhanced by $y^3 \sim 250$, while the background $\mathcal{B}$ over the resonance width drops like $1/y$. Hence, $\mathcal{S}/\mathcal{B}$ in the LRS model is expected to go up by a remarkable factor of $y^4 \sim 1500$.

The enhanced discovery reach in the LRS model could allow access to the elusive EW gauge KK modes [14]. For example, the $Z' \to \ell^+\ell^-$, $\ell = e, \mu$, golden decay modes which were quite challenging within the RS setup [14] could lead to discovery in the LRS model. Using the same cuts as in Ref. [14], a Z' with $M_{Z'} = 4-5$ TeV can be detectable with 100 fb^{-1} in the LRS scenario; the reach within the RS model is ~ 2 TeV and requires 1000 fb^{-1} [14].

Holography: AdS/CFT correspondence [16] affords a dual description of the geometric RS results in terms of a strongly coupled large N 4D gauge theory. The classical geometric relation between the 4D gauge coupling g_4 and the 5D gauge coupling g_5 [17] is

$$1/g_4^2 = \tau_{\rm UV} + \tau_{\rm IR} + \log(k/\kappa)/(kg_5^2), \tag{4}$$

where, $\tau_{\rm UV}$ and $\tau_{\rm IR}$ will be treated as small UV and IR quantum threshold corrections, respectively, and ignored. Keeping the value of g_4 fixed, reducing $kr_c\pi$ (the log) requires lowering the value of kg_5^2. In the dual CFT, this is interpreted as the contribution of CFT "quarks" to the running of external gauge couplings from the fundamental scale, M_5, down to the TeV scale. Then, $\sqrt{kg_5^2} \sim 4\pi/\sqrt{N}$ should hold between the dual theories. Thus, the LRS truncation is dual to a larger N theory, $N^{LRS} \sim yN^{RS} > N^{RS}$, making the inter-composite interactions weaker. In particular, the Higgs-CFT (KK) interactions get weaker and lead to a smaller T_{tree}.

The main contribution to S_{tree} is from the universal vertex corrections [8]. This is governed by gauge zero-KK mode mixing and scales as $1/\sqrt{N}$. The universal KK couplings to light fermions, on the other hand, scales as $\sqrt{N}$. Therefore, S remains the same under LRS truncation.

In our LRS construct, the 5D Yukawa coupling λ_5 is unscaled. This is dual to separate dynamics, characterized by a "flavor" CFT with $N_F \sim N^{RS} < N^{LRS}$.

The non-oblique and FCNC contributions depend on the amount of partial compositeness for a given N_F, in the dual picture. The amount of compositeness follows from the observed masses and mixing angles [18], once the value of λ_5 and the profile of t_R are given. The LRS partial compositeness is then unchanged by construction, and hence the non-universal observables are suppressed by truncation, leading, in general, to better agreement with the data.

In the LRS scenario, enhanced $\rho-photon$ mixing, proportional to $\sqrt{N}$ leads to larger couplings of light SM fermions to composite modes. The composite (KK) partial widths into elementary fermions scales as N, however the total width decreases as $1/N$. Therefore, $\mathcal{S} \sim N^3$ and $\mathcal{B} \sim 1/N$, over the resonance width. These effects yield stronger LRS signals at the LHC than for the RS counterpart, as $N^{LRS}/N^{RS} \gg 1$.

Here, we would like to note that other truncations motivated by other scales could still lead to improved discovery potential for warped models. We chose $M_5 \sim 1000$ TeV as a flavor scale, corresponding to a truncation factor $y \approx 6$. However, one may choose to set the UV scale at, say, 10^{10} GeV, corresponding to the mass scale of right-handed neutrinos, in a seesaw scenario for neutrino masses. Here, even for this relatively large UV scale, one still gets a significant enhancement of the light fermion signal, compared to the original RS case, since $y \approx 2$ and $\mathcal{S} \sim y^3$. Therefore, measuring the relative branching fractions of the light and heavy SM states in KK decays at the TeV scale, can potentially shed light on the size of the 5D slice, or the dual conformal window.

Even though the LRS model we presented here only addresses the flavor-weak hierarchy, a UV completion of this model can in principle accommodate the original Planck-weak hierarchy. In fact, a recent model, based on a 6D geometry with 2 warped directions [19] is a possible such completion. In Ref. [19], the LRS content resides on a 5D slice in a 6D space, where warping in one direction provides the redshift from $M_5 \sim 1000$ TeV to 1 TeV, and warping along the 6^{th} dimension provides the redshift from $M_6 \sim M_P$ down to 1000 TeV. Generalization to n-warped backgrounds, $n > 2$, have also been discussed in Ref. [19].

In summary, the LRS scenario offers a predictive framework to address flavor at a scale of order 1000 TeV, where warping generates the weak scale. This model is a truncation of the original RS model. We assumed separate bulk gauge and flavor dynamics, leading to suppression of several unwanted contributions and lesser tension with precision data. The LRS truncation leads to much improved prospects for discovery at the LHC in the dilepton channel, compared to its RS counterpart. Given the sensitivity of collider phenomenology to truncation, one may use TeV-scale data to probe the size of the 5D bulk or the dual conformal window. The LRS model may be UV completed to account for the Planck-weak hierarchy. An example of such completion has been proposed in Ref. [19].

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